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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Several block and convolutional coding options are considered which are applicable to the noncoherent detection of FH/MFSK signals in the presence of tone jamming. The tone jamming model used in this report is the worst-cast tone jamming for an uncoded system. Using decoded probability of bit error as a performance criterion, we show that large signaling alphabets yield poor performance in a tone jamming environment. Furthermore, when hard-decision quantization is used, the degradation of a coded system in tone jamming over worst-case partial band noise jamming is the same as the corresponding degradation for the uncoded system: 4.3 dB for M=2, 6.3 dB for M=4, 8.3 dB for M=8, and increasing thereafter without bound as $M \rightarrow \infty$. The poor performance of coded systems with hard-decisions in tone jamming can be improved by about 10 dB by using soft-decision quantization assisted by perfect jammer state side-information. For the binary case the results obtained by using soft-decision quantization are about 1 dB better than those obtained for the partial band noise channel, showing that the worst-case channel for the uncoded system is not necessarily the worst-case channel for a coded system when side-information is available.

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19. ABSTRACT (Continued)

The use of small alphabets and soft-decision quantization is recommended for coded FH/MFSK systems in a tone jamming environment. A major issue to be addressed in future studies concerns the type of soft-decision decoding to be used. An approach is needed that is realizable and will give performance close to that of pure soft-decisions with side-information while being free of the problems associated with obtaining perfect side information.

NRL Memorandum Report 5427

# Performance of Coded FH/MFSK in a Worst-Case Tone Jamming Channel

P. J. CREPEAU

*Communication Systems Engineering Branch*
*Information Technology Division*

September 13, 1984

NAVAL RESEARCH LABORATORY
Washington, D.C.

CONTENTS

PERFORMANCE OF CODED FH/MFSK
IN A WORST-CASE TONE JAMMING CHANNEL

## 1. INTRODUCTION

In this report we investigate several block and convolutional coding options which are applicable to noncoherent channels in the presence of tone jamming. The importance of tone jamming as an interference type arises from the fact that, in most situations, it is the worst-case interference against frequency hopped multiple frequency shift keying (FH/MFSK) modulation. In addition, tone jamming is a significant interference contribution in friendly-user networks using frequency hopped multiple access techniques where two or more users can transmit tone signals simultaneously in the same part of the frequency band.

Tone jamming strategies are detrimental to uncoded FH/MFSK systems because they change the dependence of bit error probability on signal-to-noise ratio ($E_b/N_o$) from an exponential dependence (for white Gaussian noise channels) to an inverse linear one [1]. Yet, surprisingly, few papers have been written on the subject of tone jamming for coded FH/MFSK systems. Important exceptions are the recent works of Viterbi [2] and Levitt [3,4] which give considerable insight into the improvement which can be gained by using error control codes on tone jammed channels. Both of these investigators have studied tone jamming for special classes of receivers: Viterbi has treated a simple-to-implement soft-decision quantization receiver

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using random coding arguments, while Levitt has considered a wide variety of specific codes using a pure soft-decision quantized receiver aided by perfect side-information which indicates whether or not a jamming tone is present. In the present report we consider specific codes for a hard-decision receiver and we compare the results to those of Levitt's case of a pure soft-decision receiver with jammer state information (JSI). Also we compare results on the worst-case tone jamming channel to those on the worst-case partial band noise channel [5] for both cases, hard-decisions and soft-decisions with JSI.

In Section 2 we elaborate on these introductory remarks by showing a system diagram and discussing the main distinctions between receiver types with regard to demodulators, quantizers, and decoders. In Section 3 we consider the worst-case tone and noise jamming models and review their uncoded bit error probability performance. With Section 4 we begin our analysis of the coded system and explain the approaches used for block and convolutional codes. In Section 5 all of the principal results are given for the coded system. Finally, a discussion of these results and recommendations for future work are given in Section 6.

## 2. OVERALL SYSTEM DESCRIPTION

A generic system diagram showing the basic subsystems is shown in Figure 1. The channel encoder includes all of the important coding possibilities, either convolutional or block. Since MFSK signaling is assumed, the M-ary modulator accepts $\log_2 M$ channel bits and selects one of M orthogonal tones to represent a data block. This tone is pseudo-randomly hopped in the frequency band at a rate of one hop per tone symbol. Higher or lower hopping rates are possible but we restrict the analysis to this simple, but important, case.

The coded FH/MFSK signal is transmitted over the waveform channel. In this report, two waveform channels are considered: the worst-case partial band tone jamming channel and the worst-case partial band Gaussian noise channel. Both of these are described in the next section.

On the receiver side, the signal is dehopped and sent to the MFSK demodulator. This device is composed of a bank of M energy (envelope) detectors, one matched to each of the M-ary orthogonal tones. The demodulator output is an M-dimensional vector whose elements are the M energy outputs of the energy detector bank. The M-vector output may be considered as a point in an M-dimensional output space of the demodulator.

The role of the quantizer is to partition the M-dimensional space into regions and provide the decoder with a metric (score) for each region. The metric information is also an M-dimensional vector whose M components are the

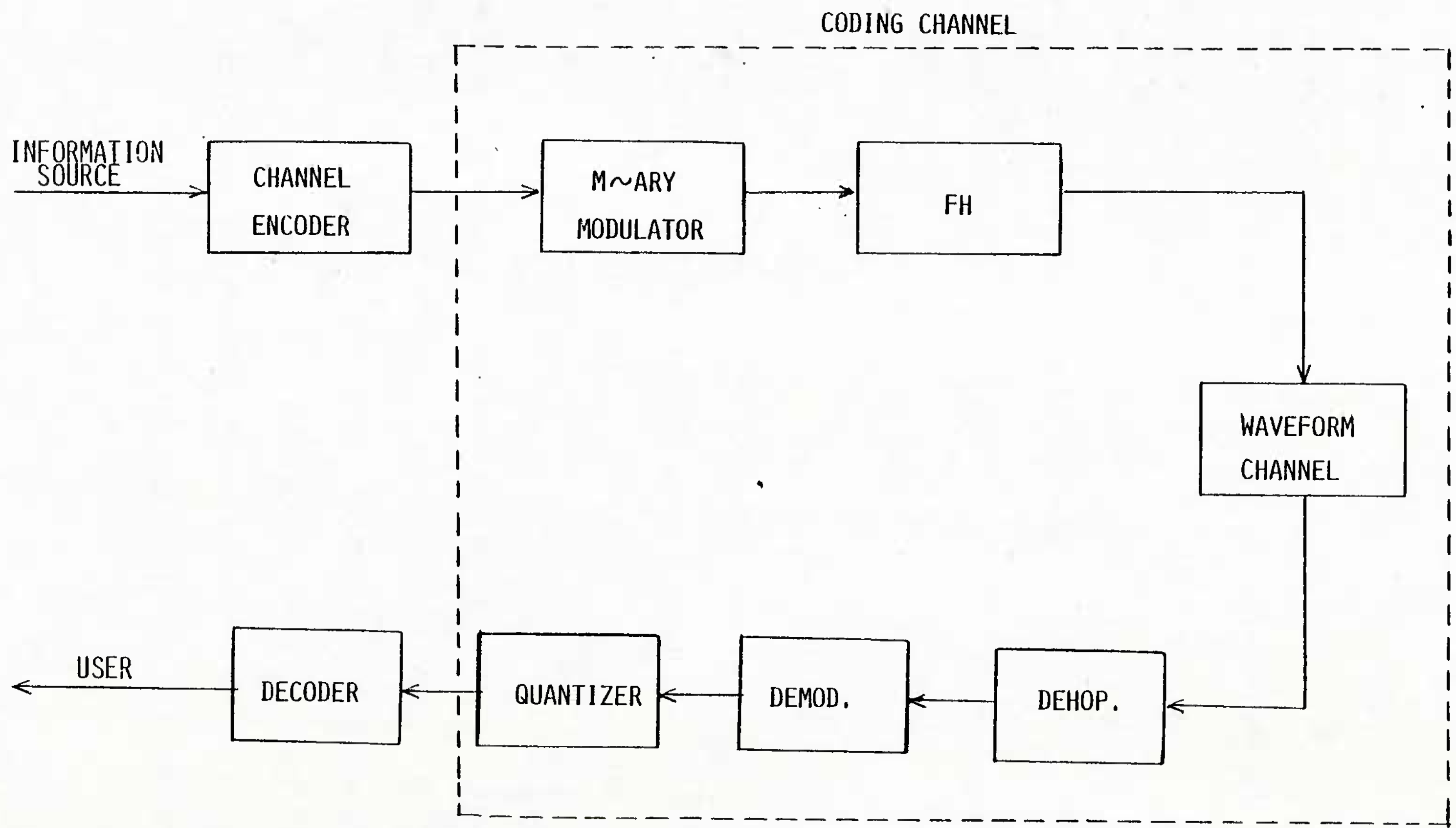


FIGURE 1. SYSTEM DIAGRAM

scores assigned to each of the M hypothesized transmitted signals. One extreme case is hard-decision quantization in which the demodulator observation space is divided into M regions defined by which of the M energy outputs is maximum in that region. The input corresponding to the largest energy is given a metric numerically equal to one while all others are zero. In the other extreme case, called pure soft-decision quantization, the energies in the M-dimensional output space are retained in analog form (unquantized) and provided to the decoder. (Any quantization scheme which partitions the M-dimensional space into more than M regions is referred to as soft-decision quantization.) Another important soft-decision technique is to create M+1 regions, with the $(M+1)^{st}$ being an erasure region. Viterbi's ratio threshold quantizer [2] is another simple soft-decision scheme, one of many possible soft-decision quantization methods.

Metric information from the quantizer is provided to the decoder. The decoder searches for codewords (for block codes) or paths (for convolutional codes) which yield the best metric. The decoder may also use side-information (if available) in order to alter the metric for a received signal. A special case of interest for jammed channels concerns the JSI mentioned in the previous section. In this idealization, the receiver knows when it has hopped into a jammed portion of the band and provides the decoder with a jamming indicator. The decoder uses this information by giving a received signal an infinite metric whenever the system hops into an unjammed part of the band (assuming no other background noise). Similarly, side-information may be used to create erasure channels. In this case the receiver senses a high interference environment and provides side-information to the decoder in the form of an erasure indicator. The decoder then assigns a zero metric to all erased signals.

For the system shown in Figure 1, the ultimate quantity of interest is the decoded probability of bit error or, at least, an approximation or a tight upper bound. To determine this quantity it is useful to decouple the coding portion of the system from the remaining part as shown by the dotted line. The coding channel (that is, all but the encoder/decoder) can be characterized by the cutoff rate parameter $R_0$ which represents the highest practically achievable code rate [6].

For orthogonal FH/MFSK signaling $R_0$ is given by

$$R_0 = \log_2 \frac{M}{1+(M-1)D} , \tag{1}$$

where D is the Chernoff bound on the probability that the incorrect metric will exceed the correct metric when a pairwise comparison is made between the transmitted signal and one of the nontransmitted signals. For the case of hard-decision quantization with no side-information, where decisions are made on channel symbols and the raw (uncoded) probability of symbol error is $P_{su}$, the Chernoff bound is easily found [7] to be

$$D = \sqrt{\frac{4P_{su}\left(1-P_{su}\right)}{M-1}} + \frac{M-2}{M-1} P_{su} . \tag{2}$$

Similar expressions exist for most coding channels of interest. These are used to obtain the coded performance results which are discussed in Section 4.

## 3. CHANNEL MODELS AND UNCODED SYSTEM PERFORMANCE

There are a variety of partial band tone jamming models which have been used in previous work [1-4]. In this report we focus upon the worst-case tone jamming channel for the uncoded FH/MFSK system. Coincidentally (and fortunately) this happens to be the simplest channel to analyze.

The worst-case tone jamming channel can be described with reference to the FH/MFSK signaling format shown in Figure 2. A total hopping bandwidth W is divided into b subbands with each tone symbol being transmitted on a different frequency hop. Within a hopping subband, one of M tones carrying $k = \log_2 M$ bits is sent with signal power S. Candidate tones are orthogonally spaced with a frequency spacing $1/T_s = R_s$, where $T_s$ is the symbol duration and $R_s$ is the symbol rate.

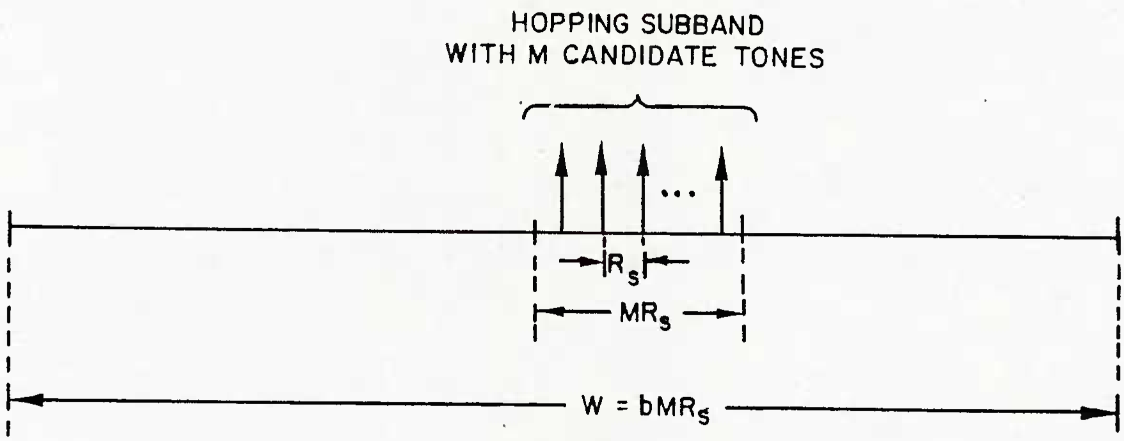


Figure 2 - FH/MFSK Signaling Format

In the worst-case jamming strategy, the jammer places tones in as many hopping subbands as possible, with a maximum of one tone per subband. The jamming tone power is taken to slightly exceed the signal power, but for purposes of analytical convenience they are assumed to be equal. In this tone jamming strategy, we further assume that the jammer has perfect knowledge of the communicator's signal power level and frequency slots. The only knowledge that the jammer lacks is the frequency hopping code.

For a total jamming power J, the jammer will attempt to force incorrect symbol decisions in n subbands by placing tones in them with power $J/n = S$. A jamming tone will cause a symbol error if it hits one of the M-1 nontransmitted tone slots in the transmission subband. The probability of symbol error is

$$P_{su} = \frac{n}{b} \frac{M-1}{M} , \tag{3}$$

where $n/b \leq 1$ is the fraction of the subbands which are jammed. For orthogonal signals, it follows that the probability of bit error is

$$P_{bu} = \frac{M}{2(M-1)} P_{su} = \frac{1}{2} \frac{n}{b} , \tag{4}$$

Since the number of the subbands jammed is

$$n = \frac{J}{S} \quad , \quad n \le b \; , \tag{5}$$

and the total number of subbands is

$$b = \frac{W}{MR_s} \tag{6}$$

where $MR_s$ is the bandwidth of one subband, it follows that (4) may be written as

$$P_{bu} = \frac{1}{2} \; \frac{J}{S} \; \frac{MR_s}{W} \quad , \qquad \frac{J}{S} \le \frac{W}{MR_s} \; . \tag{7}$$

But $S/R_s$ is the symbol energy $E_s$, and this is related to the bit energy by

$$E_s = \left(\log_2 M\right) E_b \; . \tag{8}$$

Furthermore, if $J/W$ is taken as the "equivalent" noise power spectral density $N_o$, we may rewrite (7) as

$$P_{bu} = \frac{M}{2 \log_2 M} \; \frac{1}{E_b/N_o} \quad , \quad \frac{E_b}{N_o} \ge \frac{M}{\log_2 M} \; . \tag{9}$$

For the signal-to-noise ratio region not considered in (9), that is, $E_b/N_o < M/\log_2 M$, it can be found that $P_{bu} = 1/2$. This region , however, corresponds to signal-to-noise levels that are too low to be of interest in this report. Over the range of interest, as given in (9), the dependence of $P_{bu}$ on $E_b/N_o$ is inverse linear with the probability of bit error increasing by a factor $M/2\log_2 M$ as M increases. These results are presented in both tabular form (Table I) and graphical form (Figure 3) at the end of this section.

For purposes of comparison we also consider the worst-case partial band Gaussian noise jamming channel [1,8]. This channel is characterized by constant density additive Gaussian noise over a fraction of the total hopping transmission bandwidth. Thus, the noise spectrum has density $N_o/\rho$ over a fraction $\rho$ of the band (where $0 < \rho \leq 1$) and is zero elsewhere (over a fraction $1-\rho$ of the band). We assume that the M candidate tone slots in each subband are either all interfered with or they are all noise free. As a worst-case condition, we consider only the situation where the parameter $\rho$ is chosen so as to maximize the resulting probability of error.

For uncoded FH/MFSK in a worst-case partial band Gaussian channel the results (excluding low signal-to-noise ratios) have been found in [1] as

$$P_{bu} = \frac{H}{E_b/N_o} , \tag{10}$$

where the numerator H is a constant depending on the parameter M, given in Table I. It is seen in Table I that H decreases with increasing M, giving a relatively small $E_b/N_o$ performance improvement (4.6 dB) over the binary case for large M. The inverse linear dependence of $P_{bu}$ on $E_b/N_o$ is shown in Figure 3.

Both jamming channels discussed in this section are inverse linear channels, and their only performance differences appear in the constant factors which multiply $(E_b/N_o)^{-1}$. The ratio of these factors (as it depends upon M) for the two channels of interest is given in Table I. This dB difference in Table I is reflected in Figure 3 as a shift factor which shows how much the tone channel is worse than the partial band noise channel. As M increases this difference becomes large for the uncoded case. A surprising result, shown in the Section 5, is that this same shift factor $\Delta$ is also applicable to the coded case (for any code) as long as hard-decision quantization is used.

TABLE I: DIFFERENTIAL PERFORMANCE OF WORST-CASE UNCODED TONE AND PARTIAL BAND JAMMING CHANNELS

TONE

$$P_{BU} = \frac{B}{E_B/N_O}, \quad B = \frac{M}{2\log_2 M}$$

PBJ

$$P_{BU} = \frac{H}{E_B/N_O}$$

| M | B | H | DIFFERENTIAL ADVANTAGE OF TONE OVER PBJ $\Delta = 10 \log_{10} \frac{B}{H}$ |
|---|---|---|---|
| 2 | 1 | .37 | 4.3 DB |
| 4 | 1 | .23 | 6.3 DB |
| 8 | 1.33 | .20 | 8.3 DB |
| 16 | 2 | .18 | 10.5 DB |
| 32 | 3.2 | .17 | 12.7 DB |

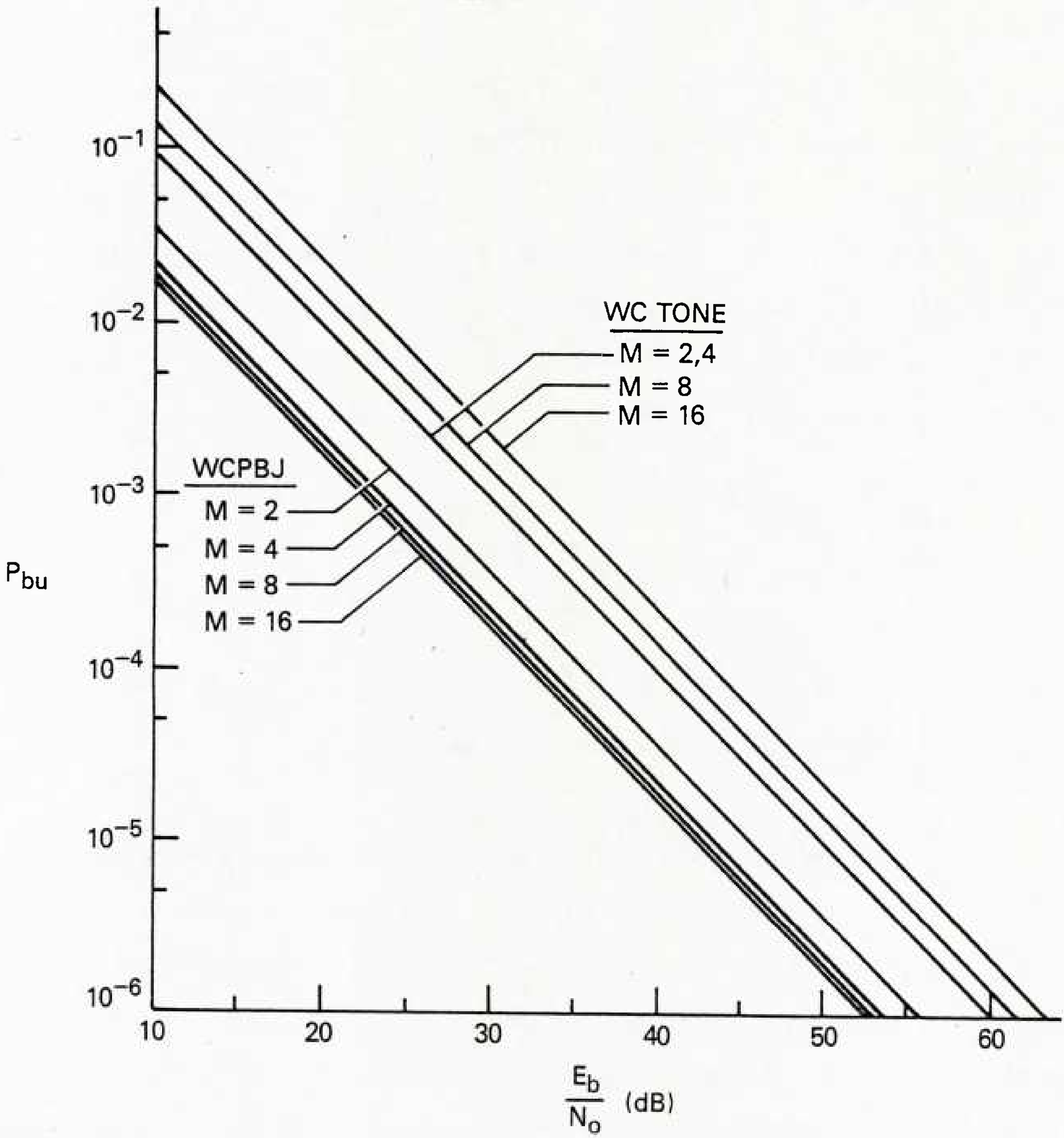


FIGURE 3 - BIT ERROR PROBABILITY FOR TONE AND WORST-CASE PARTIAL BAND NOISE CHANNELS (UNCODED CASE)

## 4. PERFORMANCE EVALUATION TECHNIQUES FOR CODED SYSTEMS

Against the sophisticated forms of jamming just described, the $E_b/N_o$ requirement of uncoded FH/MFSK is approximately 50 dB for a bit error probability of $10^{-5}$. The importance of this channel degradation can be seen by considering the maximum jamming-to-signal power ratio J/S which can be tolerated at a communication receiver. This is commonly referred to as the jamming margin and it is usually taken as a figure of merit for spread spectrum receivers. The jamming margin may be written as

$$\frac{J}{S} = \frac{PG}{E_b/N_o} , \tag{11}$$

where PG is the processing gain, that is, the ratio $W/R_b$ of the total hopped bandwidth to the information bit rate.

In (11) we see that even if frequency hopping provides a processing gain of $10^5$ (50 dB), this advantage will be lost to a jamming threat for which the $E_b/N_o$ requirement is of the order of 50 dB. With the use of error control coding, however, much of the loss of the uncoded system to jamming will be recovered. The need for coded spread spectrum systems can be understood by examination of the right hand side of (11): Spectral spreading is required for a large processing gain PG and error control coding is required for signal-to-noise efficiency (low $E_b/N_o$ requirement).

There are two basic forward error control coding techniques in common use. The first of these is convolutional coding. Analysis of the bit error probability performance of a convolutional code is usually accomplished by employing two upper bounding techniques which taken together are called the union-Chernoff bound. For most cases of interest (with decoded bit error probabilities of $10^{-3}$ or less) the error probability vs $E_b/N_o$ performance results given by these bounds are generally pessimistic by approximately one or two dB.

Using the union-Chernoff bound the decoded bit error probability $P_b$ for a convolutional code can be upper bounded by

$$P_b \le \frac{1}{2} \sum_{i=d_f}^{\infty} A_i \, D^i , \tag{12}$$

where $d_f$ is the minimum free distance of the convolutional code, $A_i$ are the code weights, and D is the Chernoff bound associated with a single use of the coding channel. The intent of (12) is to separate the code from the coding channel and to write an expression which displays the individual contribution of each part [9]. The code weights $A_i$ are tabulated in standard references (for example, [10]) and the Chernoff bounds D for tone and noise jammed channels with hard-quantized and soft-quantized (with JSI) outputs are given in [4]. In all cases, the quantity D can be related to the channel symbol signal-to-noise ratio $E_s/N_o$ which, in turn, can be related to the information bit signal-to-noise ratio $E_b/N_o$ by

$$E_s = R\left(\log_2 M\right) E_b , \tag{13}$$

where R is the code rate (in channel bits per information bit).

For block codes [9], the decoded probability of symbol error is given exactly by

$$P_s = \frac{1}{N} \sum_{i=t+1}^{N} \beta_i \binom{N}{i} P_{su}{}^{i} \left(1-P_{su}\right)^{N-i}, \tag{14}$$

where N is the block length, t is the symbol error correcting capability of the code, $P_{su}$ is the raw (uncoded) symbol error probability, and $\beta_i$ is the average number of symbol errors remaining in a decoded sequence given that the channel caused i symbol errors. For most codes of interest, $\beta_i$ is difficult to find, so it is helpful to use a simplifying approximation. This is done by noting that when more than t raw errors occur the decoder will at most correct t errors and at worst add t errors. This means that $\beta_i$ is bounded in the range

$$i-t \le \beta_i \le i+t \ , \quad i > t \ . \tag{15}$$

It has been found [9] that assigning a value of $\beta_i = i$ is a reasonable approximation, so we can write

$$P_s \simeq \frac{1}{N} \sum_{i=t+1}^{N} i \binom{N}{i} P_{su}^{\ i} \left(1-P_{su}\right)^{N-i} . \tag{16}$$

If the code symbols are the symbols associated with the M-ary orthogonal waveform channel, then the decoded probability of bit error can be found from the result of (16) and is

$$P_b = \frac{M}{2(M-1)} P_s . \tag{17}$$

For the special case of a binary channel (M=2) with a binary code we have

$$P_b \simeq \frac{1}{N} \sum_{i=t+1}^{N} i \binom{N}{i} P_{bu}^{\ i} \left(1-P_{bu}\right)^{N-i} \tag{18}$$

where $P_{bu}$ is raw bit error probability.

The block coding results given above apply to the case of hard-decision quantization only. For block codes it is difficult to implement any kind of soft-decision quantization, with the exception of the case of erasure decoding. In this report we consider only the case of hard-decision quantization for block codes, so the results of (16), (17), and (18) are appropriate expressions of the system performance.

## 5. RESULTS

We first consider the decoded bit error probability results for a tone jamming channel with hard-decision quantization. These results will serve as a baseline of comparison for all soft-decision quantization schemes. In addition, hard-decision quantization is easy to implement and for block codes it is one of the few practical approaches.

For the well-known binary convolutional codes with constraint length (K) equal to seven and code rates 1/2 and 1/3, the hard-decision results are shown (as labeled) in Figure 4. The results show that the $E_b/N_o$ requirements for the rate-1/2 and rate-1/3 codes at $10^{-5}$ decoded bit error probability are 21.8 dB and 19.0 dB respectively. The results for these cases are each 4.3 dB worse than the corresponding results for the worst-case partial band noise channel presented in [5]. In fact, the performance difference for a specific code in going from a coded partial band noise channel to a coded tone channel is the same as it is for the uncoded case. In this example we have binary codes so the performance difference is 4.3 dB.

The constant performance difference found in going from partial band noise channels with hard-decision quantization to tone channels with hard-decision quantization can be explained by examining equations (2) and (12) for convolutional codes and (16) and (18) for block codes. In all cases, the decoded bit error probability depends upon the code parameters and the raw symbol error probability of the coding channel. For fixed code parameters, a constant decoded bit error probability can be maintained by

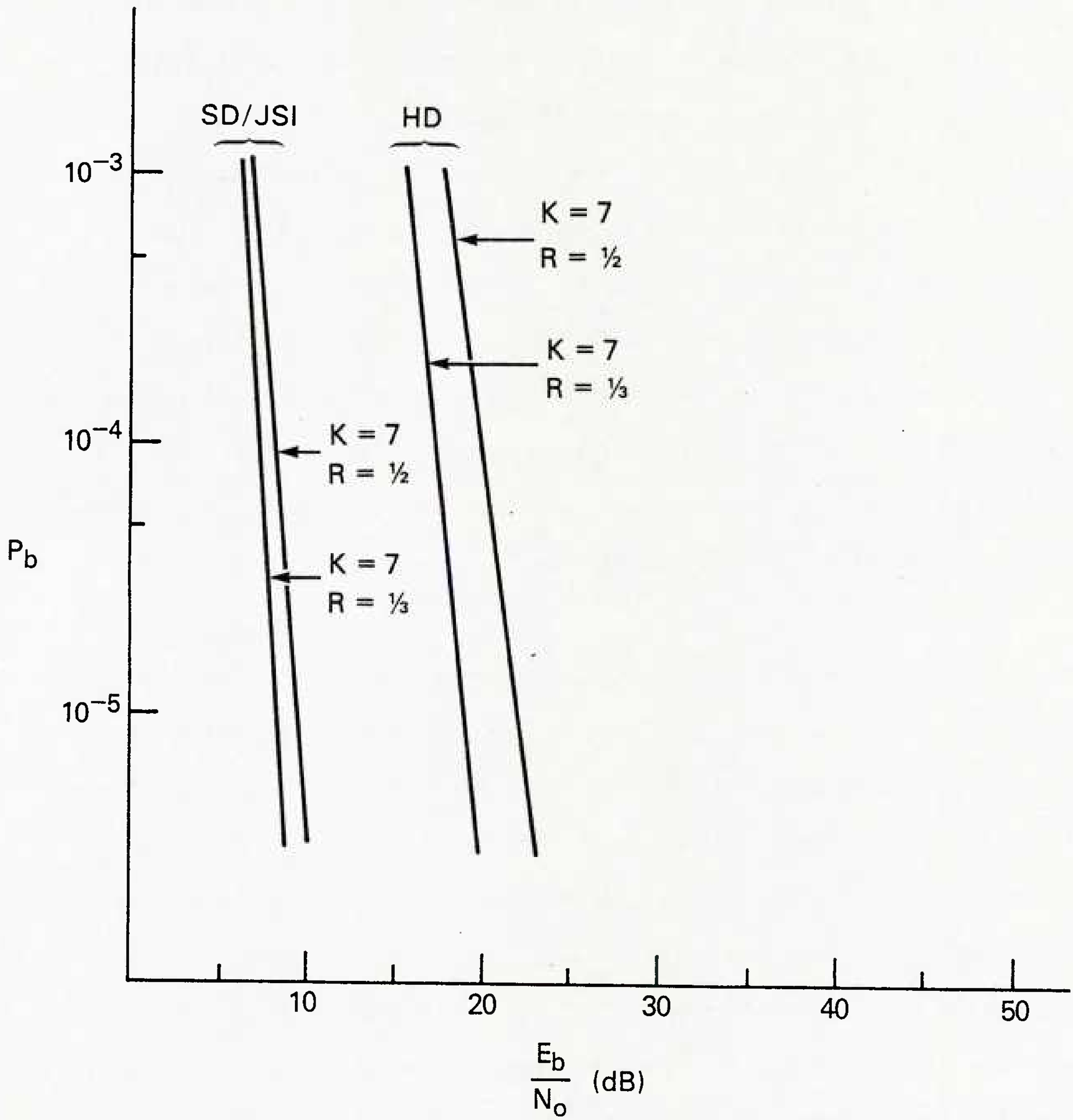


FIGURE 4 - DECODED BIT ERROR PROBABILITY FOR BINARY CONVOLUTIONAL CODES ON A TONE CHANNEL: HARD DECISIONS (HD) AND SOFT DECISIONS WITH JSI (SD/JSI)

keeping the raw symbol error probability constant in going from one channel to another. To do this we need to change the energy per channel bit according to the relationships displayed in the uncoded performance curves (Figure 3). The energy $E_b$ shown in the uncoded curves should be considered as the channel energy $E_c$ for the coded case. This channel energy is related to the information bit energy according to $E_c = RE_b$. Since the code rate R is unchanged (fixed code), the dB difference in channel bit energies is the same as the dB difference in information bit energies. Hence the coded system displays the same shift factor as the uncoded system. For large alphabet size M, this factor becomes appreciable. This leads us to the conclusion that large alphabets are not good in tone jamming environments when hard-decision quantization is used.

In Table II we show the hard-decision performance of a representative set of convolutional and block codes. The signal-to-noise requirements for a decoded bit error probability of $10^{-5}$ are given for the tone channel and the worst-case partial band channel. The first five codes shown are convolutional codes and the next four are block codes. Structural properties of all of these codes are given in [10]. The first two binary convolutional codes have been mentioned previously. The next two codes are optimal nonbinary codes. The rate-1/2 4$\sim$ary code is worse than the rate-1/2 binary code for tone jamming because of the increased alphabet size. The same may be said in comparing the rate-1/3 8$\sim$ary code with the rate-1/3 binary code. The popular dual-3 nonbinary convolutional code has poor hard-decision performance for both channels. This is true because the dual-3 code has poor distance properties. Its main virtue is its ease of implementation for soft-decision decoding. The Reed-Solomon codes, which are nonbinary block codes

TABLE II: REQUIRED $E_B/N_O$ TO ACHIEVE $P_B=10^{-5}$ FOR SEVERAL CODES ON WORST-CASE TONE AND WORST-CASE PARTIAL BAND JAMMING CHANNELS (HARD DECISIONS ONLY)

| CODE | $E_B/N_O$ FOR TONE CHANNEL | $E_B/N_O$ FOR PBJ CHANNEL |
|---|---|---|
| BINARY CONVOLUTIONAL K=7, R=1/2 | 21.8 | 17.5 |
| BINARY CONVOLUTIONAL K=7, R=1/3 | 19.0 | 14.7 |
| 4~ARY CONVOLUTIONAL K=7, R=1/2 | 23.4 | 17.1 |
| 8~ARY CONVOLUTIONAL K=7, R=1/3 | 22.2 | 13.9 |
| DUAL-3 | 31.3 | 23.0 |
| RS(7,3) | 27.1 | 18.8 |
| RS(31,15) | 23.3 | 10.6 |
| BCH(127,64) | 19.6 | 15.3 |
| GOLAY(23,12) | 23.1 | 18.8 |

with optimal distance properties, suffer from the performance loss which has been described for tone channels using higher alphabets. The RS(7,3) code is too short to be effective, while the longer RS(31,15) code is effective for the partial band noise channel but is poor for the tone channel. The 12.7 dB performance difference (between channels) is attributed to the 32 ~ ary alphabet which the RS(31,15) code uses. The binary BCH(127,64) code shows good performance for tone channels but is somewhat difficult to implement. In addition there are virtually no practical possibilities for using soft-decision quantization with this code. The popular Golay(23,12) binary code has mediocre performance. The modest distance properties of this code are not a good match for the severity of these channels.

The results shown in Table II reveal that none of the codes have adequate performance on a tone jamming channel when hard-decision quantization is used. Levitt [4] has analyzed many of these same codes for the case of pure soft-decision quantization assisted by perfect JSI. Although somewhat unrealistic, these results give the best-case results that can be obtained using an ideal decoder. Some of the key results are shown in Figure 4 and in Table III.

In Figure 4, we consider the same two binary convolutional codes (K=7, R=1/2 and K=7, R=1/3), but with soft-decision quantization and JSI. In Table III, the results for these two codes and the two optimal nonbinary convolutional codes are presented for tone and partial band noise channels, all for the case of soft-decision decoding with perfect JSI. The

TABLE III: REQUIRED $E_B/N_0$ TO ACHIEVE $P_B=10^{-5}$ FOR OPTIMAL CONVOLUTIONAL CODES ASSUMING SOFT DECISIONS AND JAMMER STATE INFORMATION

| CODE | WC/PBJ | WC/TONE |
|---|---|---|
| BINARY K=7, R=1/2 | 11.1 | 9.7 |
| BINARY K=7, R=1/3 | 10.4 | 8.9 |
| 4~ARY K=7, R=1/2 | 10.1 | 10.8 |
| 8~ARY K=7, R=1/3 | 9.0 | 11.5 |

soft-decision results reveal some remarkable features. In Figure 4 we see that for the tone channel the binary codes show a performance improvement of more than 10 dB when comparing the results of soft-decision quantization with JSI to the hard-decision results. In Table III we see that for soft-decision quantization with JSI, the performance difference between tone and partial band noise channels virtually disappears, and for the binary case the tone channel actually supports better performance. As this example reveals, the tone jamming channel is not necessarily the overall worst-case channel.

The remarkable results found by Levitt for the case of soft-decision quantization with JSI must be placed in perspective because Levitt's receiver contains an ideal decoder which is not yet realizable. The design challenge is to invent soft-decision algorithms that approach Levitt's ideal performance and can be implemented with modest complexity.

## 6. CONCLUSIONS AND RECOMMENDATIONS

In this preliminary study of the use of forward error control codes on tone jamming channels, several key results have been found:

(1) For hard-decision quantization the degradation due to alphabet size when comparing the tone channel to the worst-case partial band noise channel is the same for a coded system as for an uncoded system.

(2) The improvement resulting from the use of soft-decision quantization with JSI instead of hard-decision quantization is usually greater than 10 dB for the tone jamming channel.

(3) For binary codes, soft-decision quantization improves performance on the tone jamming channel so that it is better than the performance achievable against the worst-case partial band noise jamming channel. For nonbinary codes, performance is only slightly worse on the tone jamming channel compared to the worst-case partial band noise jamming channel.

The importance of developing good soft-decision quantizing schemes is evident from these results. The idealized structures analyzed by Levitt are not realizable but the performance improvement potential is so great that implementable receivers that approach this ideal are needed. There are many possible approaches to a soft-decision receiver. The simplest of these is the erasure detector but even this alternative is difficult to implement.

In this report we have considered a highly idealized form of tone jamming. Future studies should treat more realistic channel models, perhaps starting with the multiple-tone-jamming model discussed in [3]. Realistic models should contain a mixture of interference types and a next step would be to add Gaussian thermal noise to the tone interference. It should be recognized however, that each of these improvements in the model increase the level of analytical difficulty by a substantial amount.


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